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# Measurement of $B$ meson production cross-sections in proton-proton collisions at $\sqrt{s} = 7$ TeV



## The LHCb collaboration

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**ABSTRACT:** The production cross-sections of  $B$  mesons are measured in  $pp$  collisions at a centre-of-mass energy of 7 TeV, using data collected with the LHCb detector corresponding to a integrated luminosity of  $0.36 \text{ fb}^{-1}$ . The  $B^+$ ,  $B^0$  and  $B_s^0$  mesons are reconstructed in the exclusive decays  $B^+ \rightarrow J/\psi K^+$ ,  $B^0 \rightarrow J/\psi K^{*0}$  and  $B_s^0 \rightarrow J/\psi \phi$ , with  $J/\psi \rightarrow \mu^+ \mu^-$ ,  $K^{*0} \rightarrow K^+ \pi^-$  and  $\phi \rightarrow K^+ K^-$ . The differential cross-sections are measured as functions of  $B$  meson transverse momentum  $p_T$  and rapidity  $y$ , in the range  $0 < p_T < 40 \text{ GeV}/c$  and  $2.0 < y < 4.5$ . The integrated cross-sections in the same  $p_T$  and  $y$  ranges, including charge-conjugate states, are measured to be

$$\begin{aligned}\sigma(pp \rightarrow B^+ + X) &= 38.9 \pm 0.3 \text{ (stat.)} \pm 2.5 \text{ (syst.)} \pm 1.3 \text{ (norm.) } \mu\text{b}, \\ \sigma(pp \rightarrow B^0 + X) &= 38.1 \pm 0.6 \text{ (stat.)} \pm 3.7 \text{ (syst.)} \pm 4.7 \text{ (norm.) } \mu\text{b}, \\ \sigma(pp \rightarrow B_s^0 + X) &= 10.5 \pm 0.2 \text{ (stat.)} \pm 0.8 \text{ (syst.)} \pm 1.0 \text{ (norm.) } \mu\text{b},\end{aligned}$$

where the third uncertainty arises from the pre-existing branching fraction measurements.

**KEYWORDS:** Hadron-Hadron Scattering, Heavy quark production

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## 1 Introduction

Measurements of beauty production in multi-TeV proton-proton ( $pp$ ) collisions at the LHC provide important tests of quantum chromodynamics. State of the art theoretical predictions are given by the fixed-order plus next-to-leading logarithm (FONLL) approach [1–3]. In these calculations, the dominant uncertainties arise from the choice of the renormalisation and factorisation scales, and the assumed  $b$ -quark mass [4]. The primary products of  $b\bar{b}$  hadronisation are  $B^+$ ,  $B^0$ ,  $B_s^0$  and their charge-conjugate states (throughout the paper referred to as  $B$  mesons) formed by one  $\bar{b}$  quark bound to one of the three light quarks ( $u$ ,  $d$  and  $s$ ). Accurate measurements of the cross-sections probe the validity of the production models. At the LHC,  $b\bar{b}$  production has been studied in inclusive  $b \rightarrow J/\psi X$  decays [5, 6] and semileptonic [7, 8] decays. Other measurements, using fully reconstructed  $B$  mesons, have also been performed by the LHCb and CMS collaborations [9–12].

In this paper, a measurement of the production cross-sections of  $B$  mesons (including their charge-conjugate states) is presented. This study is performed in the transverse momentum range  $0 < p_T < 40$  GeV/ $c$  and rapidity range  $2.0 < y < 4.5$  using data, corresponding to a integrated luminosity of  $0.36 \text{ fb}^{-1}$ , collected in  $pp$  collisions at centre-of-mass energy of 7 TeV by the LHCb experiment. The  $B$  mesons are reconstructed in the exclusive decays  $B^+ \rightarrow J/\psi K^+$ ,  $B^0 \rightarrow J/\psi K^{*0}$  and  $B_s^0 \rightarrow J/\psi \phi$ , with  $J/\psi \rightarrow \mu^+ \mu^-$ ,  $K^{*0} \rightarrow K^+ \pi^-$  and  $\phi \rightarrow K^+ K^-$ .

The LHCb detector [13] is a single-arm forward spectrometer covering the pseudorapidity range  $2 < \eta < 5$ , designed for the study of particles containing  $b$  or  $c$  quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the  $pp$  interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream. The combined tracking system has momentum resolution  $\Delta p/p$  that varies from 0.4% at 5 GeV/ $c$  to 0.6% at

100 GeV/ $c$ , and impact parameter resolution better than 20  $\mu\text{m}$  for transverse momentum higher than 3 GeV/ $c$ . Charged hadrons are identified using two ring-imaging Cherenkov (RICH) detectors. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

The events used in this analysis are selected by a two-stage trigger system [14]. The first stage is hardware based whilst the second stage is software based. At the hardware stage events containing either a single muon or a pair of muon candidates, with high transverse momentum, are selected. In the subsequent software trigger the decision of the single-muon or dimuon hardware trigger is confirmed and a muon pair with an invariant mass consistent with the known  $J/\psi$  mass [15] is required. To reject high-multiplicity events with a large number of  $pp$  interactions, global event cuts on the hit multiplicities of subdetectors are applied.

## 2 Candidate selection

The selection of  $B$  meson candidates starts by forming  $J/\psi \rightarrow \mu^+\mu^-$  decay candidates. These are formed from pairs of oppositely-charged particles that are identified as muons and have  $p_T > 0.7 \text{ GeV}/c$ . Good quality of the reconstructed tracks is ensured by requiring the  $\chi^2/\text{ndf}$  of the track fit to be less than 4, where ndf is the number of degrees of freedom of the fit. The muon candidates are required to originate from a common vertex and the  $\chi^2/\text{ndf}$  of the vertex fit is required to be less than 9. The mass of the  $J/\psi$  candidate is required to be around the known  $J/\psi$  mass [15], between 3.04 and 3.14  $\text{GeV}/c^2$ .

Kaons used to form  $B^+ \rightarrow J/\psi K^+$  candidates are required to have  $p_T$  larger than 0.5  $\text{GeV}/c$ . Information from the RICH detector system is not used in the selection since the  $B^+ \rightarrow J/\psi \pi^+$  decay is Cabibbo suppressed. Candidates for  $K^{*0} \rightarrow K^+\pi^-$  and  $\phi \rightarrow K^+K^-$  decays are formed from pairs of oppositely-charged hadron candidates. Since the background levels of these two channels are higher than for  $B^+ \rightarrow J/\psi K^+$  decay, the hadron identification information provided by the RICH detectors is used. Kaons used to form  $K^{*0}$  candidates in the  $B^0 \rightarrow J/\psi K^{*0}$  channel and  $\phi$  candidates in the  $B_s^0 \rightarrow J/\psi \phi$  channel are selected by cutting on the difference between the log-likelihoods of the kaon and pion hypotheses provided by the RICH detectors ( $\text{DLL}_{K\pi} > 0$ ). The pions used to form  $K^{*0}$  candidates are required to be inconsistent with the kaon hypothesis ( $\text{DLL}_{\pi K} > -5$ ). The same track quality cuts used for muons are applied to kaons and pions. The  $K^{*0}$  and  $\phi$  meson candidates are constructed requiring a good vertex quality ( $\chi^2/\text{ndf} < 16$ ) and  $p_T > 1.0 \text{ GeV}/c$ . The masses of the  $K^{*0}$  and  $\phi$  candidates are required to be consistent with their known masses [15], in the intervals 0.826 – 0.966  $\text{GeV}/c^2$  and 1.008 – 1.032  $\text{GeV}/c^2$ , respectively.

The  $J/\psi$  candidate is combined with a  $K^+$ ,  $K^{*0}$  or  $\phi$  candidate to form a  $B^+$ ,  $B^0$  or  $B_s^0$  meson, respectively. A vertex fit [16] is performed that constrains the daughter particles to originate from a common point and the mass of the muon pair to match the known  $J/\psi$  mass [15]. The  $\chi^2/\text{ndf}$  returned by this fit is required to be less than 9. To further reduce

the combinatorial background due to particles produced in the primary  $pp$  interaction, only  $B$  candidates with a decay time larger than 0.3 ps, which corresponds to about 6 times the decay time resolution, are kept. In the  $B^0 \rightarrow J/\psi K^{*0}$  samples, duplicate candidates are found that share the same  $J/\psi$  particle but have pion tracks that are reconstructed several times from one track. In these cases only one of the candidates is randomly retained. Duplicate candidates of other sources in the other decay modes occur at a much lower rate and are retained. Finally, the fiducial requirements  $0 < p_T < 40$  GeV/ $c$  and  $2.0 < y < 4.5$  are applied to the  $B$  meson candidates.

### 3 Cross-section determination

The differential production cross-section for each  $B$  meson species is calculated as

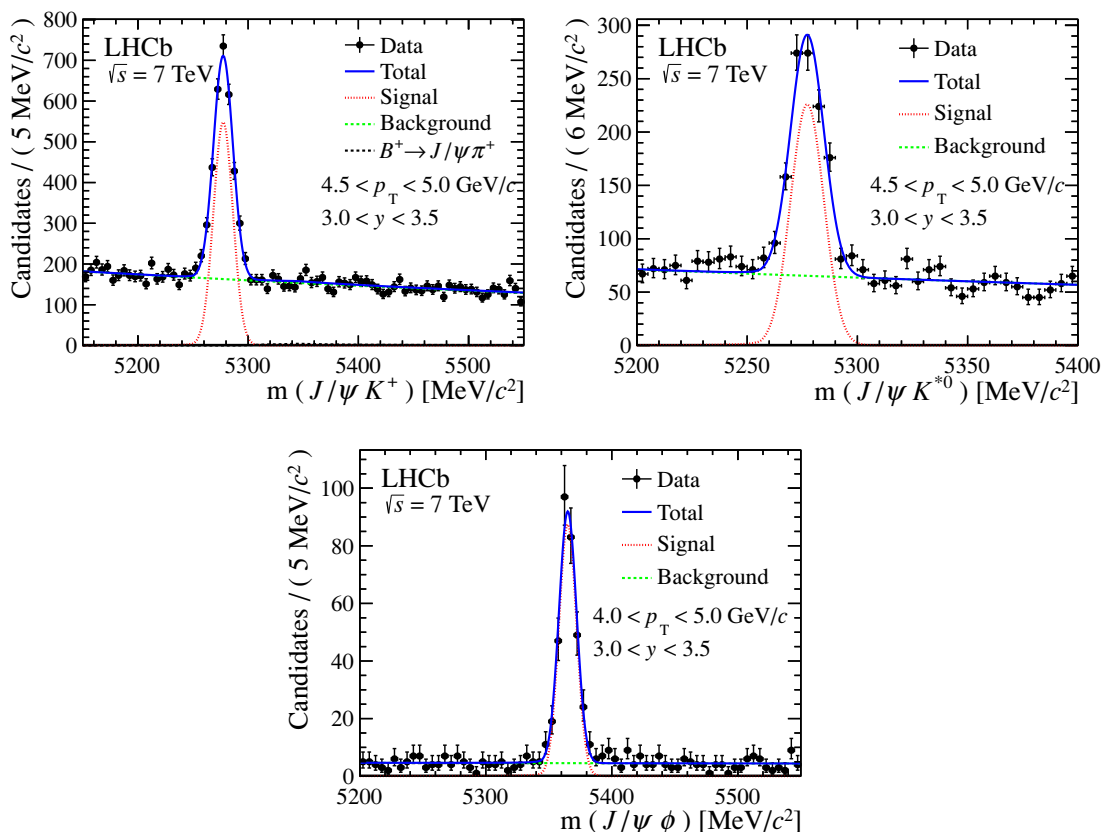
$$\frac{d^2\sigma(B)}{dp_T dy} = \frac{N_B(p_T, y)}{\epsilon_{\text{tot}}(p_T, y) \mathcal{L}_{\text{int}} \mathcal{B}(B \rightarrow J/\psi X) \Delta p_T \Delta y},$$

where  $N_B(p_T, y)$  is the number of reconstructed signal candidates in a given  $(p_T, y)$  bin,  $\epsilon_{\text{tot}}(p_T, y)$  is the total efficiency in a given  $(p_T, y)$  bin,  $\mathcal{L}_{\text{int}}$  is the integrated luminosity,  $\mathcal{B}(B \rightarrow J/\psi X)$  is the product of the branching fractions of the decays in the complete decay chain, and  $\Delta p_T$  and  $\Delta y$  are the widths of the bin. The width of each  $y$  bin is fixed to 0.5 while the widths of the  $p_T$  bins vary to allow for sufficient number of candidates in each bin.

The signal yield in each bin of  $p_T$  and  $y$  is determined using an extended unbinned maximum likelihood fit to the invariant mass distribution of the reconstructed  $B$  candidates. The fit model includes two components: a double-sided Crystal Ball function to model the signal and an exponential function to model the combinatorial background. The former is an extension of the Crystal Ball function [17] that has tails on both the low- and the high-mass side of the peak described by separate parameters, which are determined from simulation. For the  $B^+$  channel, the  $K$ - $\pi$  misidentified  $B^+ \rightarrow J/\psi \pi^+$  decay is modelled by a shape that is found to fit the distribution of simulated events. The invariant mass distributions of the selected  $B$  candidates and the fit results in one  $p_T$  and  $y$  bin are shown in figure 1.

For the  $B^0 \rightarrow J/\psi K^{*0}$  and  $B_s^0 \rightarrow J/\psi \phi$  decay channels, an additional non-resonant S-wave component (where the  $K^+\pi^-$  and the  $K^+K^-$  originate directly from  $B^0$  and  $B_s^0$  decays, and not via  $K^{*0}$  or  $\phi$  resonances) is also present. The amount of this component present in each case is determined from an independent fit to the  $K^+\pi^-$  or  $K^+K^-$  mass distribution, respectively, integrating the  $p_T$  and  $y$  range. The signal component is described by a relativistic Breit-Wigner function, and the S-wave background by a phase space function. From the fit results, the S-wave fractions are determined to be  $\sim 6\%$  for  $B^0 \rightarrow J/\psi K^+\pi^-$  and  $\sim 3\%$  for  $B_s^0 \rightarrow J/\psi K^+K^-$  decays. The yields of  $B$  mesons are then corrected according to the S-wave fractions.

The geometrical acceptance as well as the reconstruction and selection efficiencies, except for the hadron identification efficiencies, are determined using simulated signal events. The  $pp$  collisions are generated using PYTHIA 6.4 [18] with a specific LHCb configuration [19]. Decays of hadronic particles are described by EVTGEN [20], in which final state



**Figure 1.** Invariant mass distributions of the selected candidates for (*top left*)  $B^+$  and (*top right*)  $B^0$  decays, both in the range  $4.5 < p_T < 5.0$  GeV/c,  $3.0 < y < 3.5$ , and (*bottom*)  $B_s^0$  decay in the range  $4.0 < p_T < 5.0$  GeV/c,  $3.0 < y < 3.5$ . The results of the fit to the model described in the text are superimposed. The Cabibbo-suppressed background is barely visible in the top left plot.

radiation is generated using PHOTOS [21]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [22, 23] as described in ref. [24]. The hadron identification efficiencies are measured using tracks from the decay  $D^{*+} \rightarrow D^0 \pi^+$  with  $D^0 \rightarrow K^- \pi^+$ , selected without using information from the RICH detectors [25].

Only candidates where the  $J/\psi$  is responsible for the trigger decision are used. The trigger efficiency is measured in data using the tag and probe method described in ref. [14].

The luminosity is measured using Van der Meer scans and a beam-gas imaging method [26]. The integrated luminosity of the data sample used in this analysis is determined to be  $362 \pm 13 \text{ pb}^{-1}$ .

The branching fraction  $\mathcal{B}(B^0 \rightarrow J/\psi K^{*0})$  measured by the Belle collaboration [27] is used in the determination of the  $B^0$  cross-section, since it includes the effect of the S-wave interference, while other measurements do not. The measurement of  $\mathcal{B}(B_s^0 \rightarrow J/\psi \phi)$  given in ref. [28] is used in the determination of the  $B_s^0$  cross-section. Since this branching fraction measurement used the average ratio of fragmentation fractions  $f_s/f_d$  from ref. [29, 30], the result in this paper cannot be taken as an independent measurement of  $f_s/f_d$ . The other branching fractions are obtained from ref. [15].

Source	$B^+$	$B^0$	$B_s^0$
Signal fit model	2.5	1.3	1.2
Fit range	0.1	1.0	0.4
Non-resonant background	—	2.2	1.9
Combinatorial background	0.6	0.8	0.3
Bin size	0.1 – 10.9	0.1 – 19.3	0.1 – 13.2
Duplicate candidates	—	3.1	—
Trigger efficiency	2.4 – 7.9	2.6 – 7.9	2.6 – 6.5
Tracking efficiency	2.4 – 7.4	4.4 – 8.3	4.4 – 8.5
Vertex quality cut	1.0	0.9	0.2
Muon identification	0.7 – 4.9	0.8 – 5.0	0.8 – 5.8
Hadron identification	—	1.0	0.8
Angular distribution	—	0.1 – 0.3	0.1 – 4.7
$p_T$ distribution	—	0 – 24.4	—
Branching fractions	3.3	12.3	10.0
Luminosity	3.5	3.5	3.5

**Table 1.** Relative systematic uncertainties (in %), given as single values or as ranges, when they depend on the  $(p_T, y)$  bin.

## 4 Systematic uncertainties

The measurements are affected by systematic uncertainties in the determination of the signal yields, efficiencies, branching fractions and luminosity, as summarised in table 1. The total systematic uncertainty is obtained from the sum in quadrature of all contributions.

Uncertainties on the signal yields arise from imperfect knowledge of the signal shape, non-resonant background and finite size of the bins. The uncertainty from the signal shape is estimated by comparing the fitted and generated signal yields in simulation. The non-resonant background ratios determined in this analysis are compared with those from measurements with angular fits [28] and the differences are assigned as systematic uncertainties. By varying the  $p_T$  or  $y$  binning, the uncertainty for changing the binning in  $p_T$  is found to be small while that for  $y$  is non-negligible in the low  $y$  bin. An uncertainty is assigned due to the procedure of removal of duplicate candidates in  $B^0 \rightarrow J/\psi K^{*0}$  events. For the other modes this effect is found to be negligible. The uncertainties from the background shape, misidentified  $B^+ \rightarrow J/\psi \pi^+$  background and mass fit range are small.

Uncertainties on the efficiencies arise from the trigger, tracking, particle identification, angular distribution,  $p_T$  spectrum and vertex fit quality cut. The systematic uncertainty from the trigger efficiency is evaluated by comparing the efficiency measured using a trigger-unbiased sample of simulated  $J/\psi$  events with that determined from the simulation. The effect of the global event cuts in the trigger is found to be negligible. The tracking efficiencies are estimated with a tag and probe method [31] using  $J/\psi \rightarrow \mu^+ \mu^-$  events in both data and simulation. The simulated efficiencies, used to determine the cross-section, are

corrected according to the differences between data and simulation. The tracking uncertainty includes two components: the first is from the data-simulation difference correction; the second is due to the uncertainty on the hadronic interaction length of the detector used in the simulation. Possible systematic biases in the determination of the hadron identification efficiency are estimated using simulated events and comparing the true efficiency with that obtained by applying the same procedure as for the data. The muon identification uncertainty is estimated by comparing the efficiency in simulation with that measured, on data, using a tag and probe method. The systematic uncertainties due to the uncertainties on the angular distributions of  $B^0$  and  $B_s^0$  decays [15, 32] are taken into account by simulating the effect of varying the central values of the polarization amplitudes by  $\pm 1$  sigma. In the first  $p_T$  bin of the  $B^0$  sample, the agreement of the  $p_T$  distributions between data and simulation is not as good as in the other bins. The discrepancy is assigned as an additional uncertainty for that bin. The vertex fit quality cut uncertainty is estimated from the data to simulation comparison. By calculating the signal yields and efficiencies separately for data taken with two magnet polarities, the results are found to be stable.

The systematic uncertainties from the branching fractions are calculated with their correlations taken into account. Since the  $\mathcal{B}(B^0 \rightarrow J/\psi K^{*0})$  and  $\mathcal{B}(B_s^0 \rightarrow J/\psi \phi)$  have been measured with sizeable uncertainty, the corresponding uncertainties are listed separately in the cross-section results. The absolute luminosity scale is measured with 3.5% uncertainty, which is dominated by the beam current uncertainty [26].

## 5 Results and conclusion

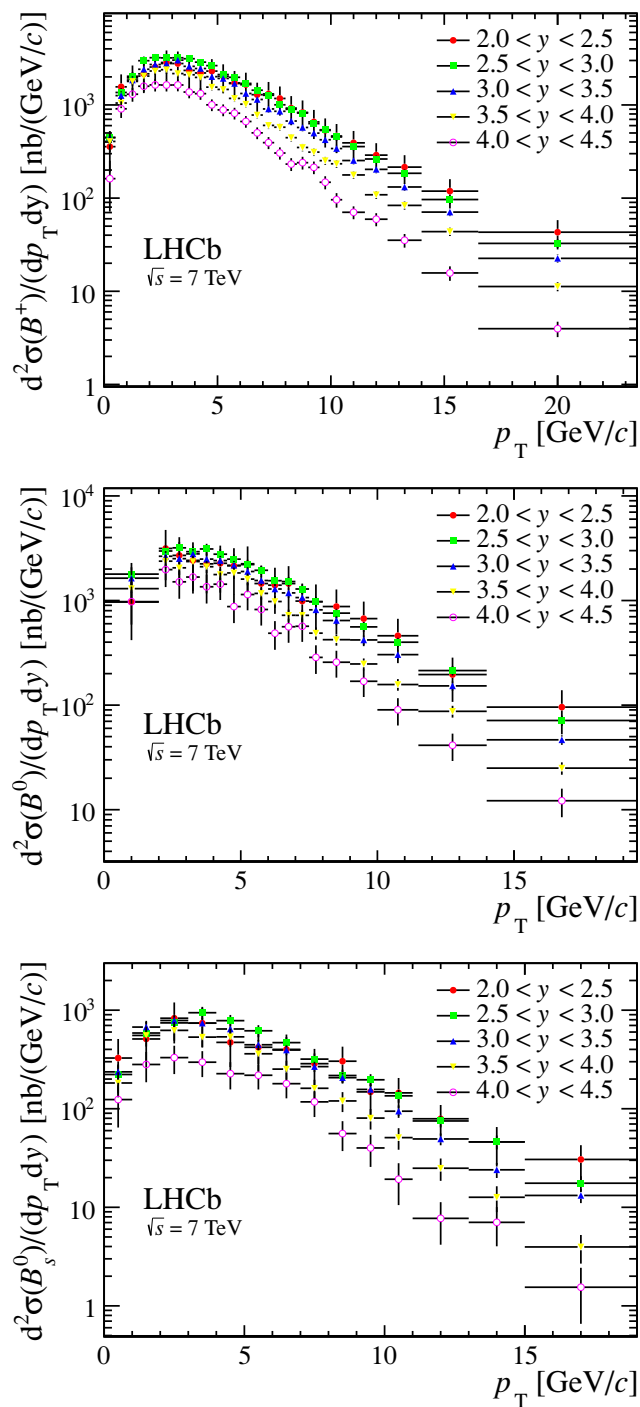
The measured differential production cross-sections of  $B$  mesons in bins of  $p_T$  and  $y$  are shown in figure 2. These results are integrated separately over  $y$  and  $p_T$ , and compared with the FONLL predictions [3], as shown in figure 3 and figure 4, respectively. The hadronisation fractions  $f_u = f_d = (33.7 \pm 2.2)\%$  and  $f_s = (9.0 \pm 0.9)\%$  from ref. [29] are used to fix the overall scale of FONLL. The uncertainty of the FONLL computation includes the uncertainties on the  $b$ -quark mass, renormalisation and factorisation scales, and CTEQ 6.6 [33] parton distribution functions. Good agreement is seen between the FONLL predictions and measured data.

The integrated cross-sections of the  $B$  mesons with  $0 < p_T < 40$  GeV/ $c$  and  $2.0 < y < 4.5$  are

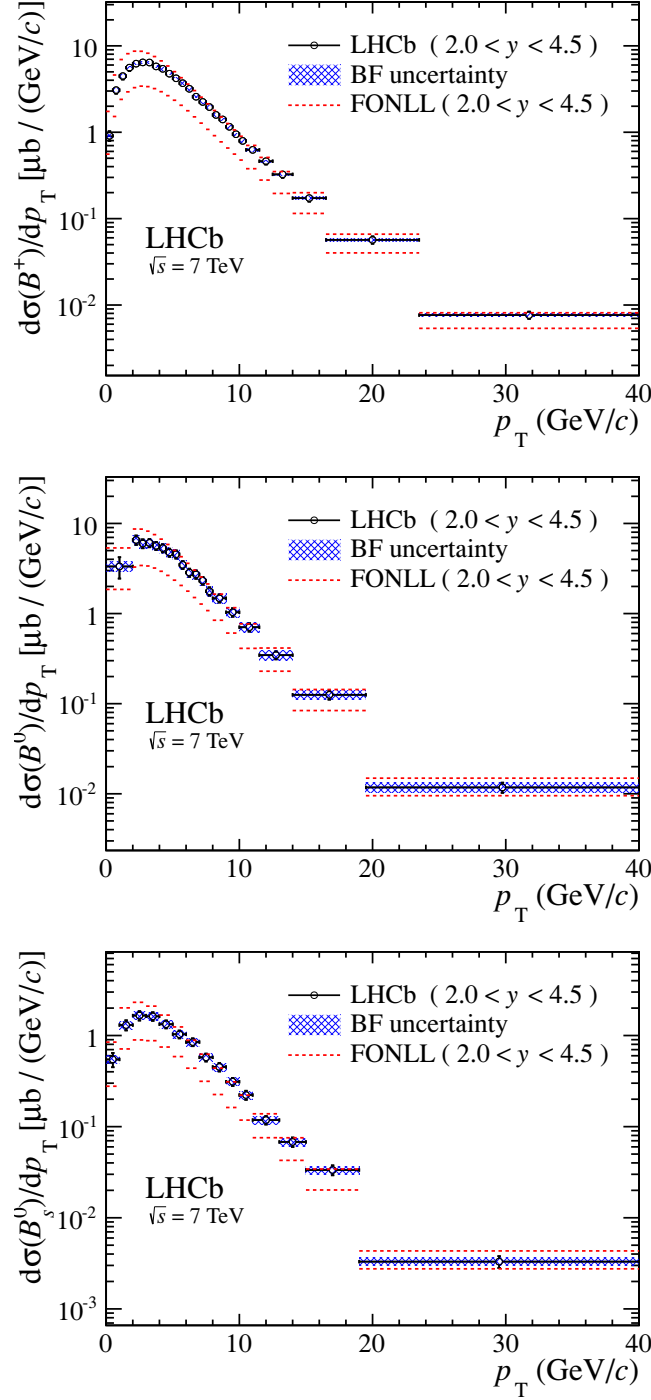
$$\begin{aligned}\sigma(pp \rightarrow B^+ X) &= 38.9 \pm 0.3 (\text{stat.}) \pm 2.5 (\text{syst.}) \pm 1.3 (\text{norm.}) \text{ } \mu\text{b}, \\ \sigma(pp \rightarrow B^0 X) &= 38.1 \pm 0.6 (\text{stat.}) \pm 3.7 (\text{syst.}) \pm 4.7 (\text{norm.}) \text{ } \mu\text{b}, \\ \sigma(pp \rightarrow B_s^0 X) &= 10.5 \pm 0.2 (\text{stat.}) \pm 0.8 (\text{syst.}) \pm 1.0 (\text{norm.}) \text{ } \mu\text{b},\end{aligned}$$

where the third uncertainties arise from the uncertainties of the branching fractions used for normalisation. The  $B^+$  result is in good agreement with a previous measurement by LHCb [9]. These represent the first measurements of  $B^0$  and  $B_s^0$  meson production cross-sections in  $pp$  collisions in the forward region at centre-of-mass energy of 7 TeV.

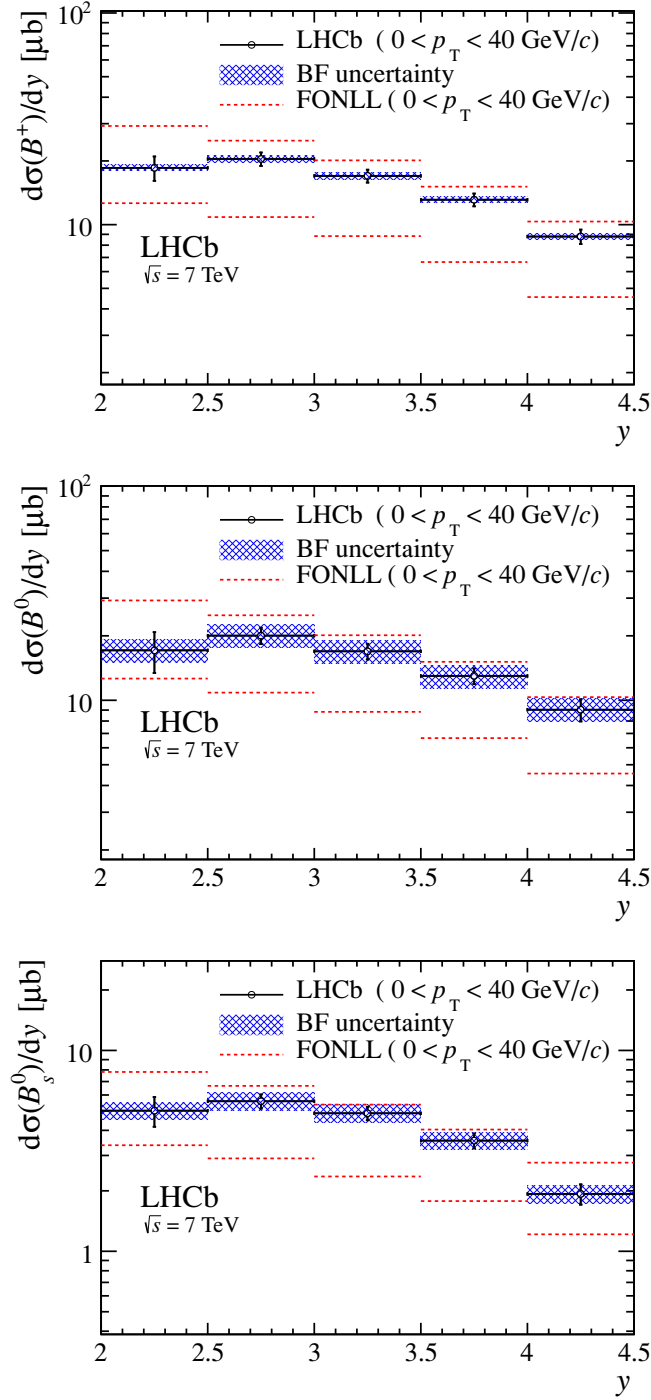




**Figure 2.** Differential production cross-sections for (*top*)  $B^+$ , (*middle*)  $B^0$  and (*bottom*)  $B_s^0$  mesons, as functions of  $p_T$  for each  $y$  interval.



**Figure 3.** Differential production cross-sections for (*top*)  $B^+$ , (*middle*)  $B^0$  and (*bottom*)  $B_s^0$  mesons, as functions of  $p_T$  integrated over the whole  $y$  range. The open circles with error bars are the measurements (not including uncertainties from normalisation channel branching fractions and luminosity) and the blue shaded areas are the uncertainties from the branching fractions. The red dashed lines are the upper and lower uncertainty limits of the FONLL computation [3].



**Figure 4.** Differential production cross-sections for (*top*)  $B^+$ , (*middle*)  $B^0$  and (*bottom*)  $B_s^0$  mesons, as functions of  $y$  integrated over the whole  $p_T$  range. The black open circles with error bars are the measurements (not including uncertainties from normalisation channel branching fractions and luminosity) and the blue shaded areas are the uncertainties from the branching fractions. The red dashed lines are the upper and lower uncertainty limits of the FONLL computation [3].

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